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(54) **POWER AMPLIFIER MODULE**

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CPC **H03F 1/0211** (2013.01); **H03F 1/0266** (2013.01); **H03F 1/301** (2013.01); **H03F 1/56** (2013.01); **H03F 3/193** (2013.01); **H03F 3/195** (2013.01); **H03F 3/211** (2013.01); **H03F 3/24** (2013.01); **H03F 3/45179** (2013.01); **H03F 3/45475** (2013.01); **H03F 3/72** (2013.01); **H03F 2200/222** (2013.01); **H03F 2200/318** (2013.01); **H03F 2200/387** (2013.01); **H03F 2200/447** (2013.01); **H03F 2200/451** (2013.01); **H03F 2200/555** (2013.01); **H03F 2203/45112** (2013.01); **H03F 2203/45528** (2013.01); **H03F 2203/45536** (2013.01); **H03F 2203/7206** (2013.01); **H03F 2203/7215** (2013.01)

(58) **Field of Classification Search**

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See application file for complete search history.

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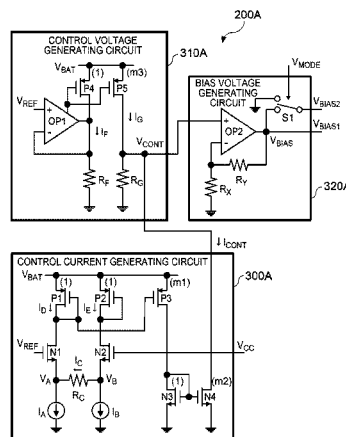
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(57) **ABSTRACT**

Consumption current may be reduced in a power amplifier module in which a power supply voltage supplied to a power amplification transistor is controlled according to the level of output power. The power amplifier module includes an amplification transistor supplied with the power supply voltage according to the level of output power to amplify a radio-frequency signal, a bias control circuit for generating a bias voltage according to the power supply voltage, and a bias circuit for supplying a bias current according to the bias voltage to the amplification transistor, wherein current flowing through the amplification transistor when the radio-frequency signal is not input is varied according to the level of output power.

21 Claims, 10 Drawing Sheets



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FIG. 1

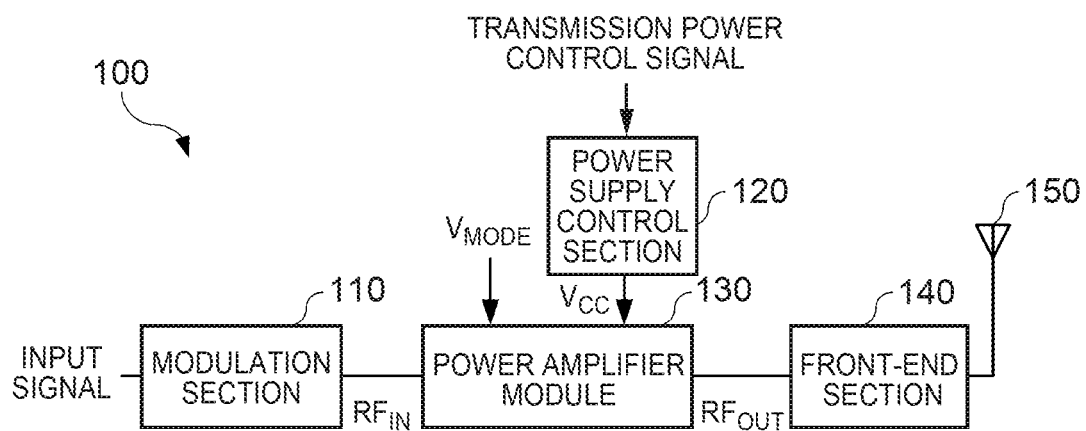


FIG. 2

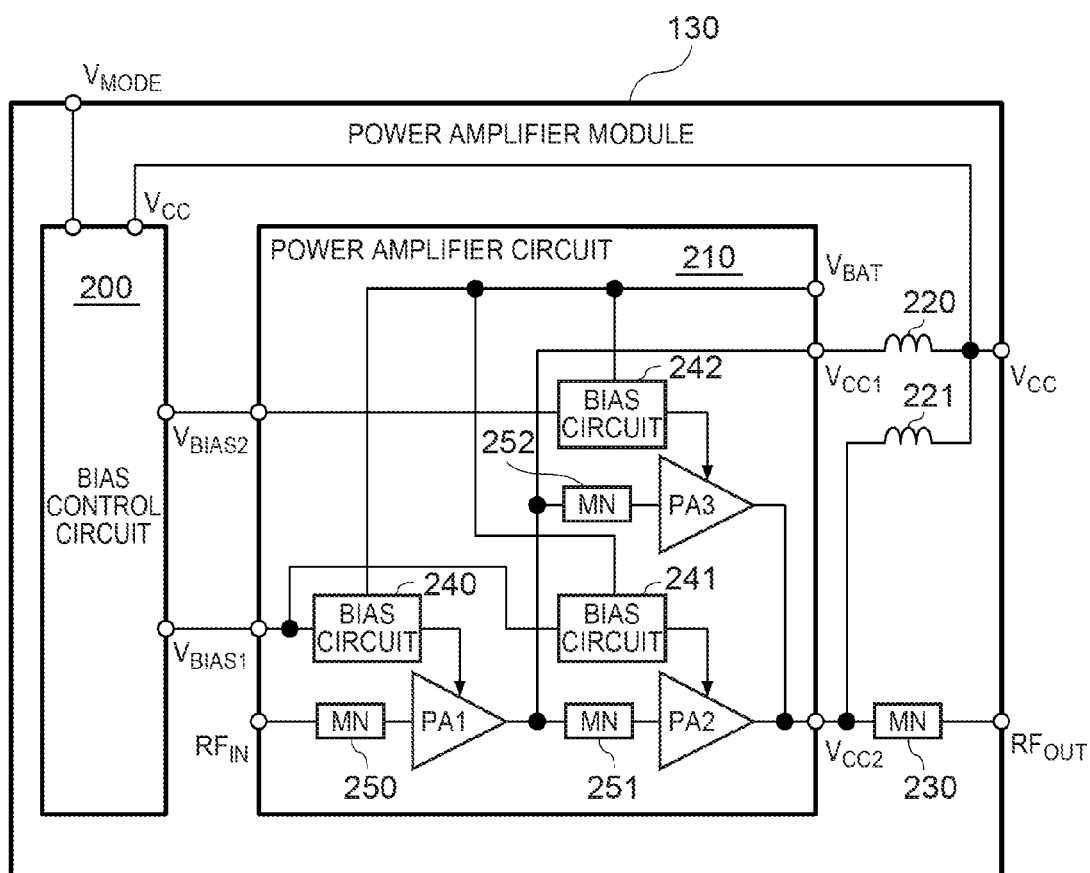
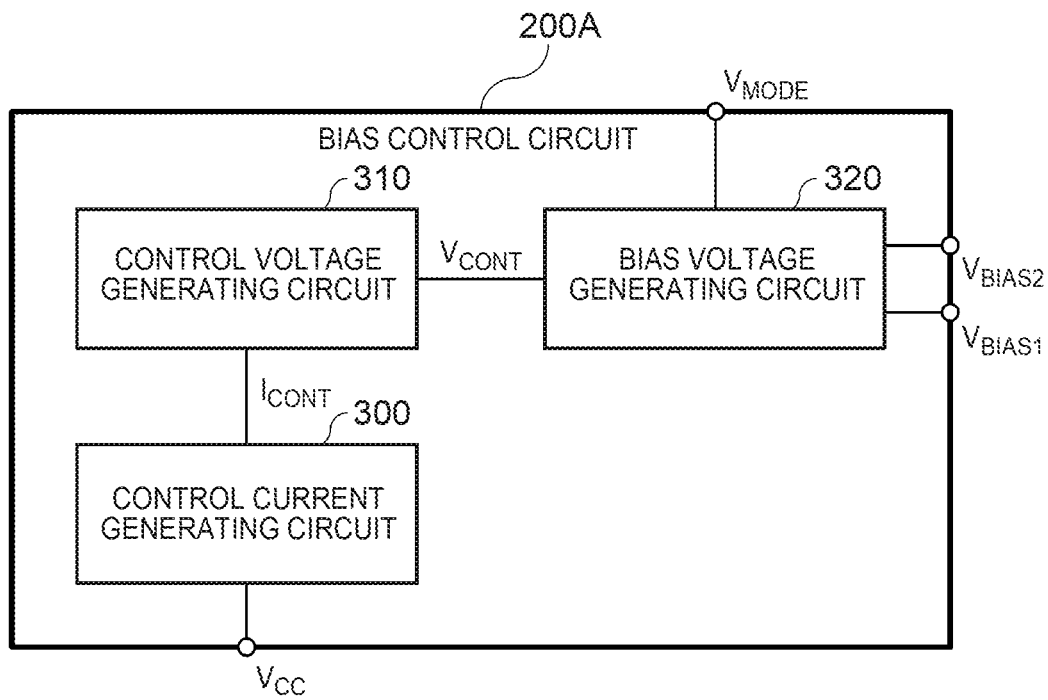
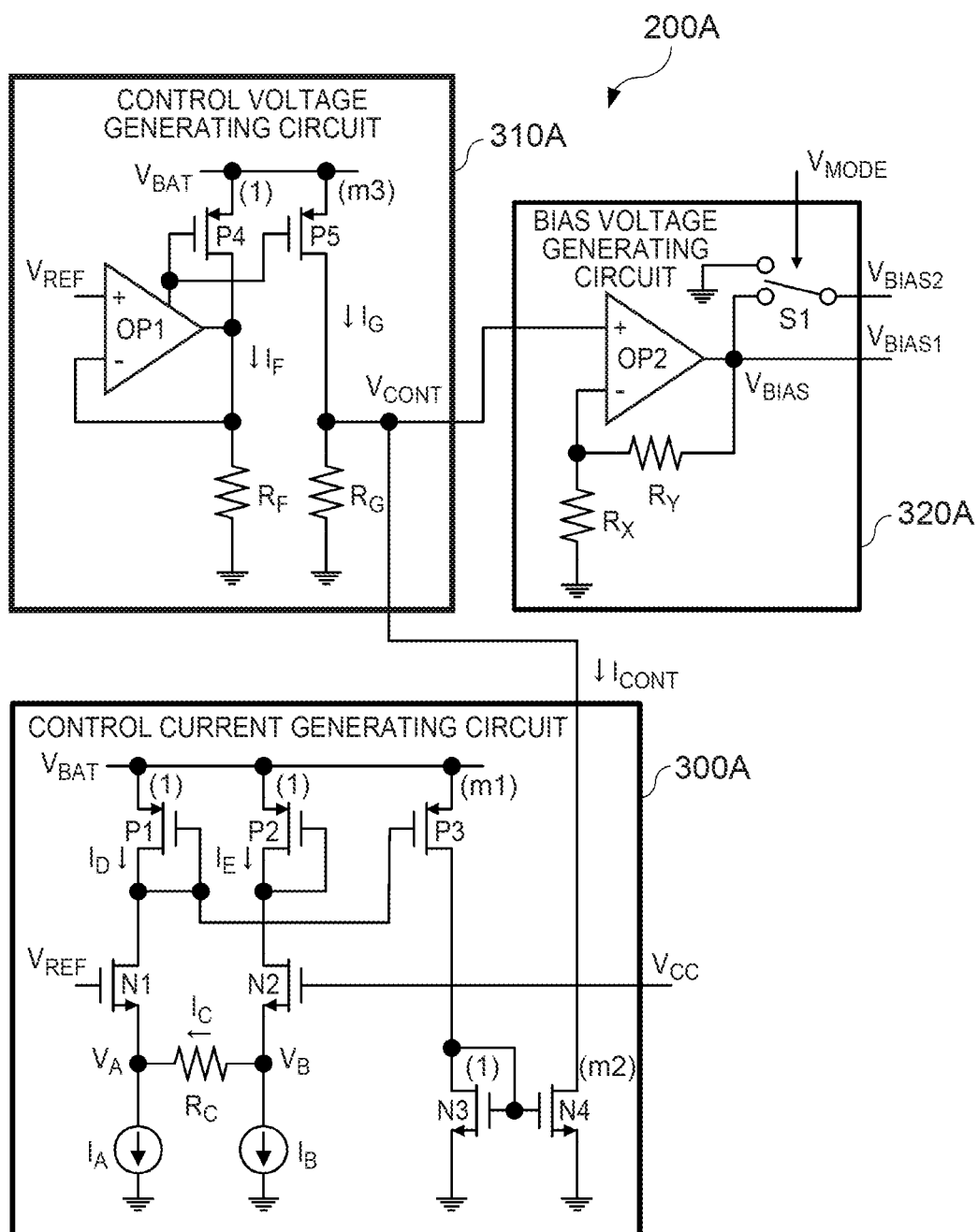


FIG. 3





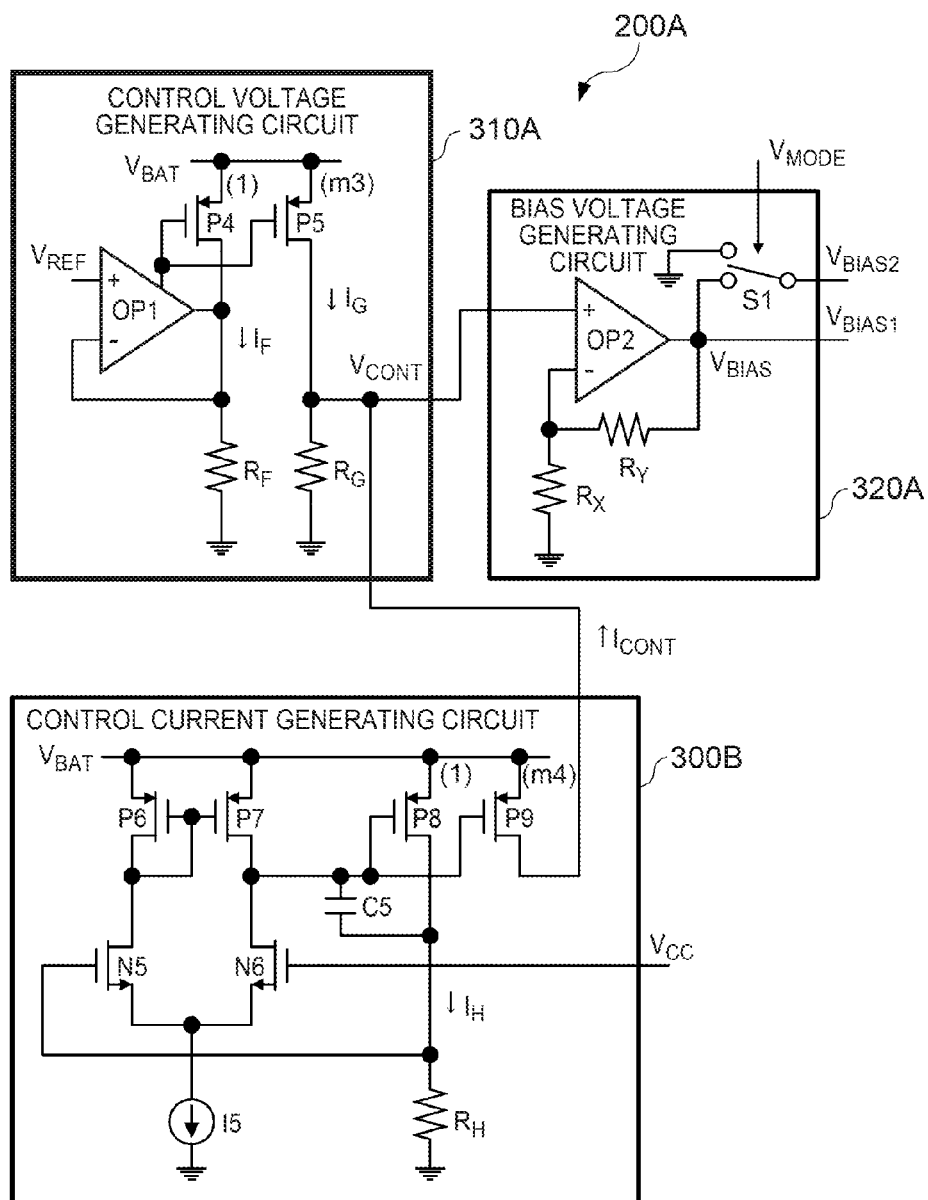


FIG. 6

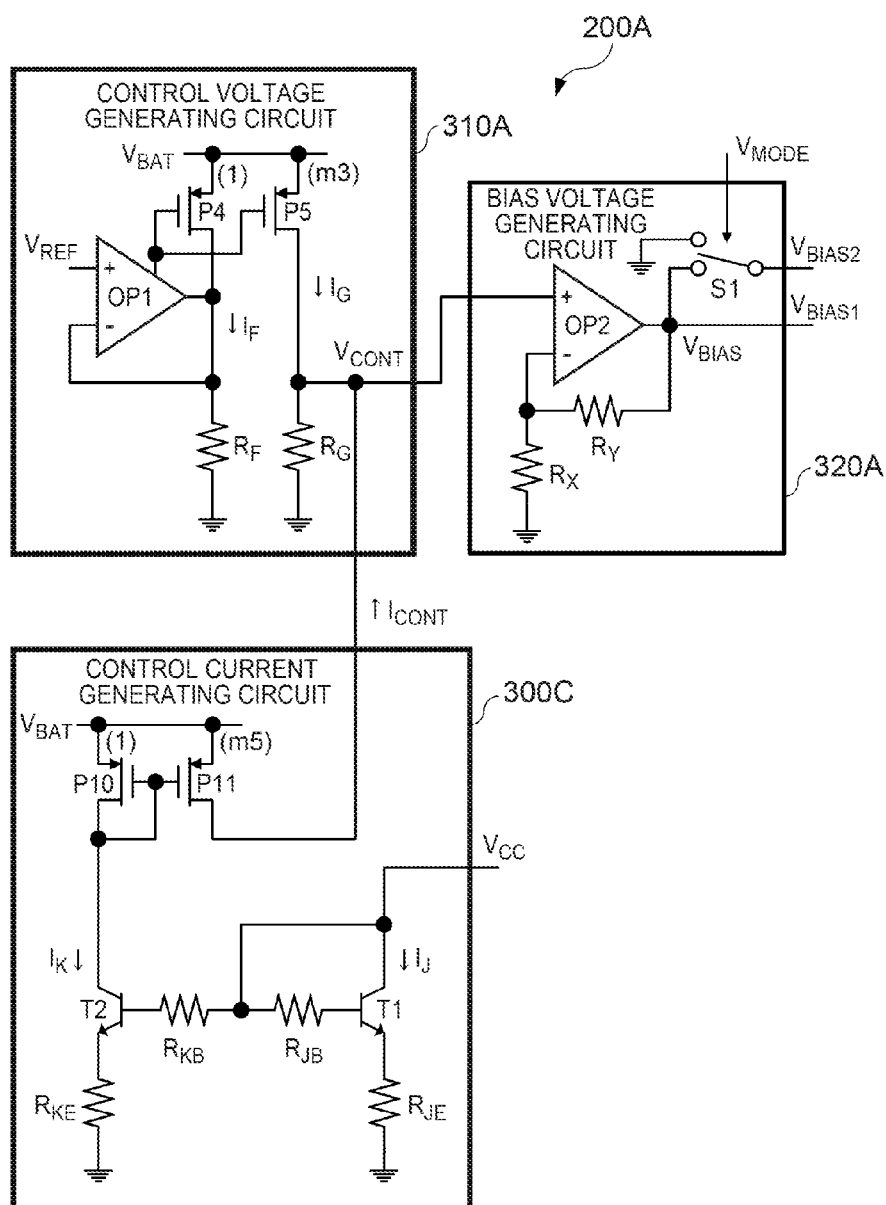


FIG. 7

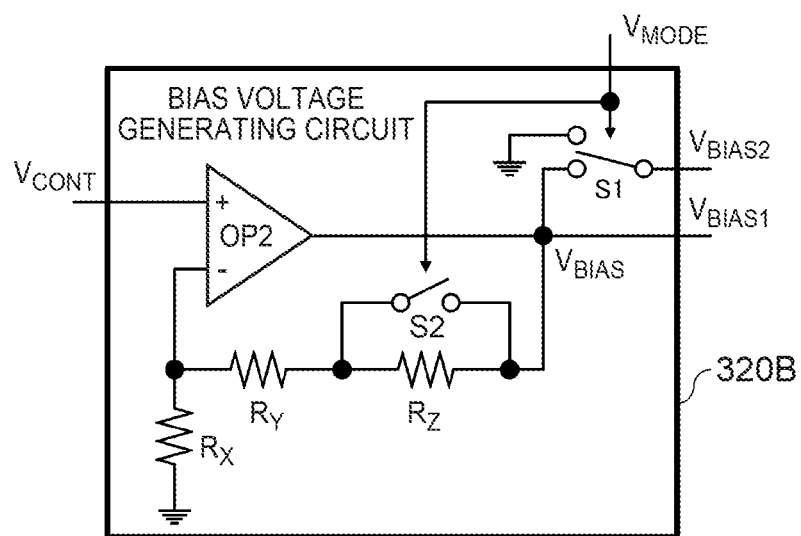
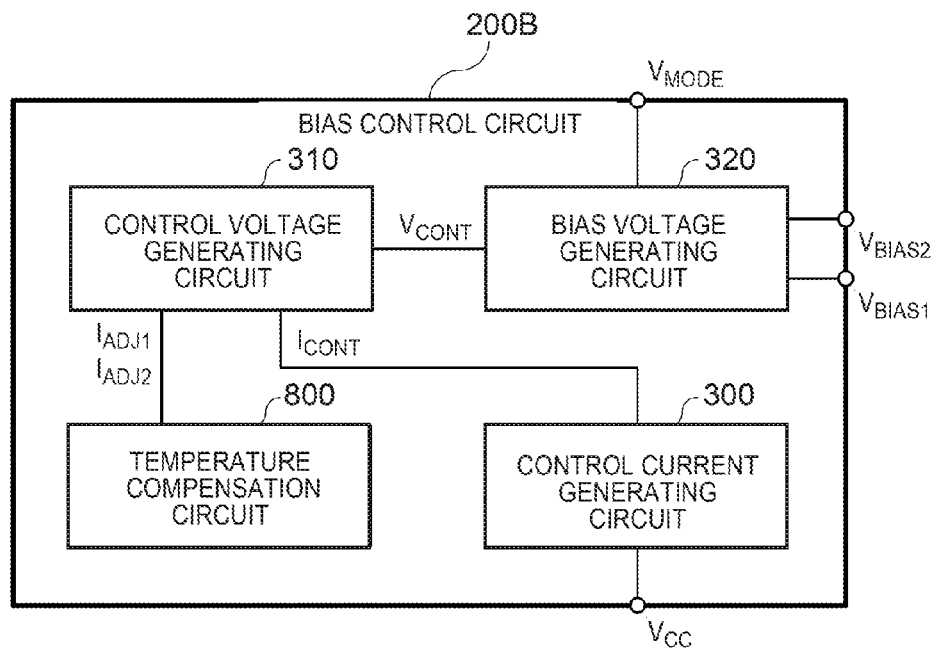


FIG. 8



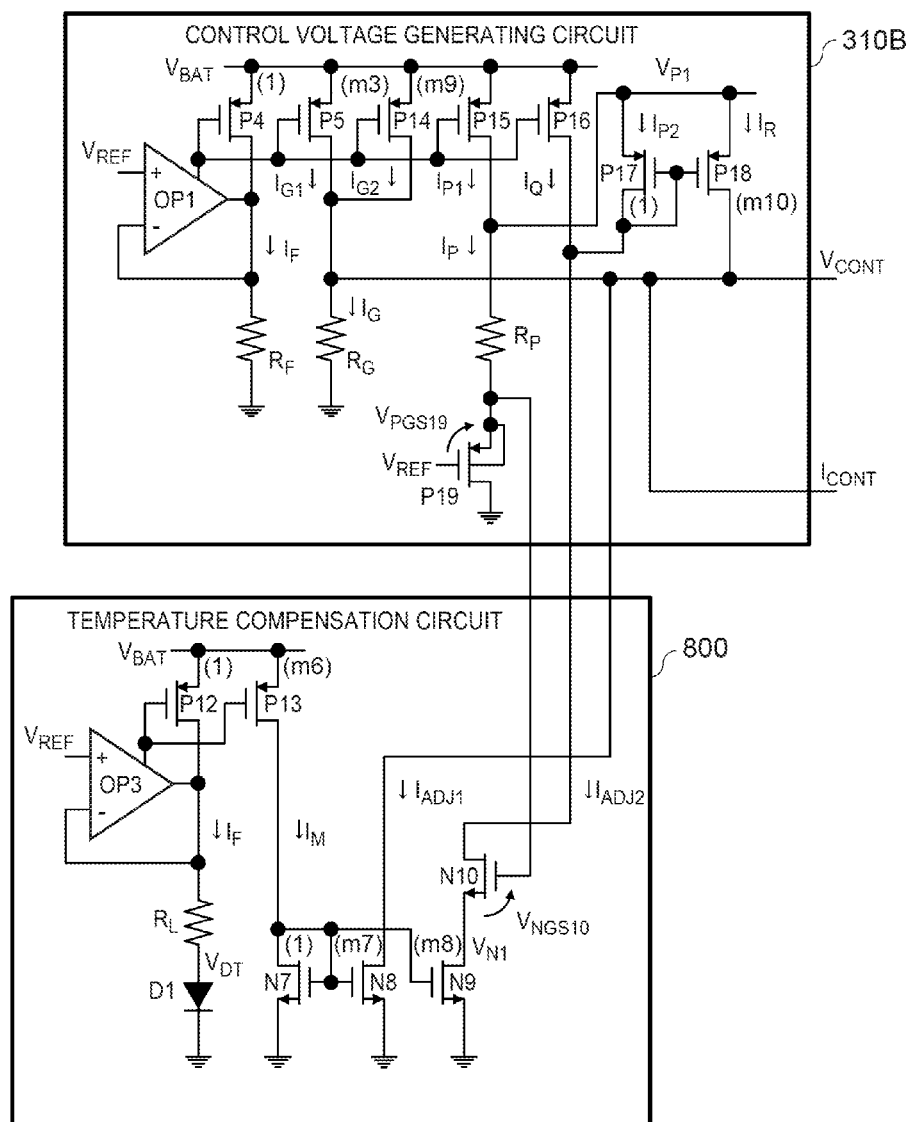


FIG. 10

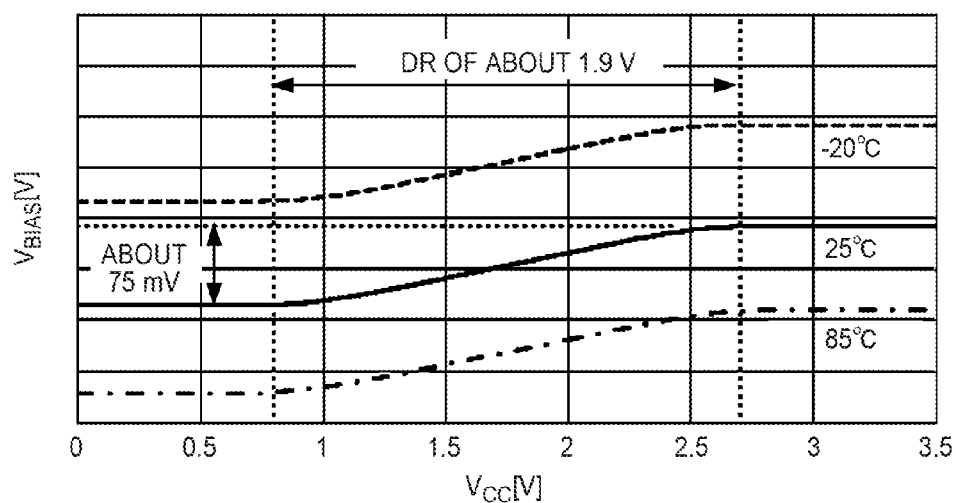
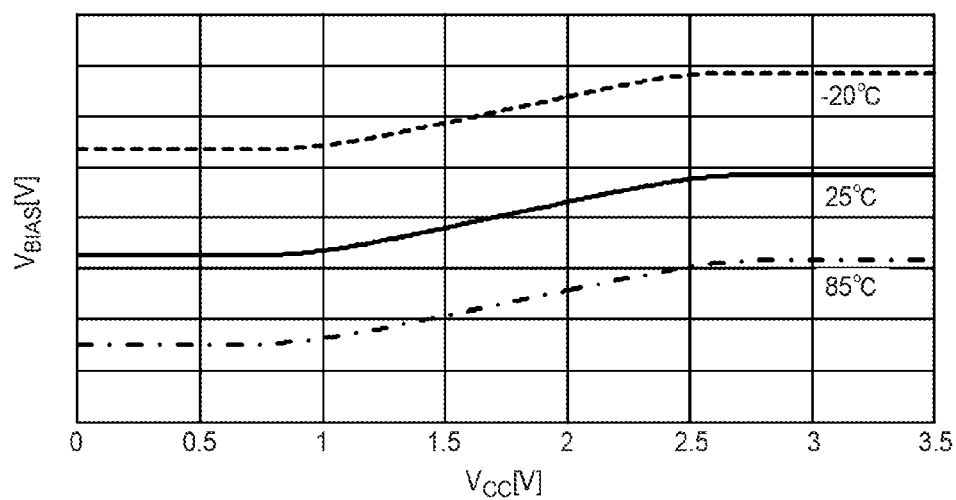


FIG. 11



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POWER AMPLIFIER MODULE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a power amplifier module.

2. Background Art

In a mobile communication device such as a mobile phone, a power amplifier module is used to amplify the power of a signal to be transmitted to a base station. Patent Document 1 discloses a configuration for variably controlling a power supply voltage supplied to a power amplification transistor in such a power amplifier module according to the level of required output power.

Patent Document 2 discloses a configuration for controlling a bias current in a power amplifier module. Specifically, in the configuration disclosed in Patent Document 2, when the peak value of collector voltage of a power amplification transistor becomes higher than a preset voltage due to a load variation, a bias circuit is controlled to increase the bias current.

CITATION LIST

Patent Documents

[Patent Document 1] JP 2006-270146 A

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SUMMARY OF THE INVENTION

In the configuration disclosed in Patent Document 1, the power supply voltage is controlled according to the level of required output power, but the control of bias current is not considered. In other words, in the configuration disclosed in Patent Document 1, the reduction in current (idle current) flowing through the power amplification transistor during a no-signal condition is not considered. In the configuration disclosed in Patent Document 2, the control of bias current is performed only when the load is changed, and the reduction in idle current is not considered.

The present invention has been made in view of these circumstances, and consumption current may be reduced in a power amplifier module in which a power supply voltage supplied to a power amplification transistor is controlled according to the level of output power.

A power amplifier module according to one aspect of the present invention includes an amplification transistor supplied with a power supply voltage according to the level of output power to amplify a radio-frequency signal, a bias control circuit for generating a bias voltage according to the power supply voltage, and a bias circuit for supplying a bias current according to the bias voltage to the amplification transistor, wherein current flowing through the amplification transistor when the radio-frequency signal is not input is varied according to the level of output power.

According to the present invention, consumption current can be reduced in the power amplifier module in which the power supply voltage supplied to the power amplification transistor is controlled according to the level of output power.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram showing a configuration example of a transmitting unit including a power amplifier module according to one embodiment of the present invention.

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FIG. 2 is a diagram showing an example of a configuration of a power amplifier module.

FIG. 3 is a diagram showing an example of a configuration of a bias control circuit.

FIG. 4 is a diagram showing an example of a configuration of a control current generating circuit, a control voltage generating circuit, and a bias voltage generating circuit in the bias control circuit.

FIG. 5 is a diagram showing another example of a configuration of a control current generating circuit, a control voltage generating circuit, and a bias voltage generating circuit in a bias control circuit.

FIG. 6 is a diagram showing still another example of a configuration of a control current generating circuit, a control voltage generating circuit, and a bias voltage generating circuit in a bias control circuit.

FIG. 7 is a diagram showing another example of a configuration of a bias voltage generating circuit.

FIG. 8 is a diagram showing another example of a configuration of a bias control circuit.

FIG. 9 is a diagram showing an example of a configuration of a temperature compensation circuit and a control voltage generating circuit in the bias control circuit shown in FIG. 8.

FIG. 10 is a graph showing simulation results in a low power mode in the configuration shown in FIG. 9.

FIG. 11 is a graph showing simulation results in a high power mode in the configuration shown in FIG. 9.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

One embodiment of the present invention will be described below with reference to the accompanying drawings. FIG. 1 is a diagram showing a configuration example of a transmitting unit including a power amplifier module as one embodiment of the present invention. A transmitting unit **100** is used, for example, in a mobile communication device such as a mobile phone, to transmit various signals such as voice and data to a base station. Note that the mobile communication device also has a receiving unit for receiving signals from the base station, but the description thereof will be omitted here.

As shown in FIG. 1, the transmitting unit **100** is configured to include a modulation section **110**, a power supply control section **120**, a power amplifier module **130**, a front-end section **140**, and an antenna **150**.

The modulation section **110** modulates an input signal based on a modulation scheme such as HSUPA (High Speed Uplink Packet Access) or LTE (Long Term Evolution) to generate a radio frequency (RF) signal for radio transmission. For example, the RF signal is in a range of several hundred MHz to several GHz.

The power supply control section **120** controls the level of power supply voltage V_{CC} supplied to the power amplifier module **130** based on a transmission power control signal. For example, the power supply control section **120** generates a power supply voltage V_{CC} according to a level of output power (power level) of the power amplifier module **130**. Specifically, the power supply voltage V_{CC} increases as the level of output power increases. For example, the power supply control section **120** can include a DC-DC converter for generating a target level of power supply voltage V_{CC} from a battery voltage. The transmission power control signal is generated based on, for example, an adaptive power control (APC) signal transmitted from the base station. For example, the base station can measure a signal from the

mobile communication device to transmit the APC signal to the mobile communication device as a command for adjusting transmission power in the mobile communication device to an appropriate level.

The power amplifier module **130** amplifies the power of an RF signal (RF_{IN}) output from the modulation section **110** to a level required for transmission to the base station, and outputs an amplified signal (RF_{OUT}). The power supply voltage V_{CC} supplied to the power amplifier module **130** is controlled by the power supply control section **120**. The power amplifier module **130** operates in a power mode according to a power mode control voltage V_{MODE} for controlling the power mode. For example, the power modes include a low power mode (LPM) and a high power mode (HPM).

The front-end section **140** performs filtering for amplified signals, switching from/to signals received from the base station, and the like. The amplified signal output from the front-end section **140** is transmitted to the base station through the antenna **150**.

FIG. 2 is a diagram showing an example of the configuration of the power amplifier module **130**. The power amplifier module **130** includes a bias control circuit **200**, a power amplifier circuit **210**, inductors **220** and **221**, and a matching circuit (MN) **230**.

The bias control circuit **200** generates bias voltages (V_{BIAS1} , V_{BIAS2}) according to the level of power supply voltage V_{CC} supplied to the power amplifier module **130**. Further, the bias control circuit **200** controls the output of bias voltage based on the power mode control voltage V_{MODE} . Specifically, for example, the bias control circuit **200** sets the bias voltage V_{BIAS2} to a zero level in the low power mode. The details of the bias control circuit **200** will be described later.

The power amplifier circuit **210** includes power amplification transistors PA1, PA2, and PA3, bias circuits **240** to **242**, and matching circuits (MN) **250** to **252**. The power amplifier circuit **210** is, for example, composed of heterojunction bipolar transistors (HBT).

The power amplification transistors PA1 to PA3 are NPN transistors for amplifying the power of an RF signal. The power amplification transistor PA1 constitutes a drive stage, and the power amplification transistors PA2 and PA3 constitute a power stage. An RF signal output from the power amplification transistors PA2 and PA3 in the power stage is output as an amplified signal (RF_{OUT}) through the matching circuit **230**.

The power supply voltage V_{CC} is supplied to the collector of the power amplification transistor PA1 through the inductor **220**. Further, a bias current is supplied from the bias circuit **240** to the base of the power amplification transistor PA1. Further, the RF signal is input to the base of the power amplification transistor PA1 through the matching circuit **250**. Then, the power amplification transistor PA1 outputs a signal, obtained by amplifying the RF signal, from the collector of power amplification transistor PA1.

The power supply voltage V_{CC} is supplied to the collector of the power amplification transistor PA2 through the inductor **221**. Further, the bias current is supplied from the bias circuit **241** to the base of the power amplification transistor PA2. Further, the RF signal output from the power amplification transistor PA1 is input to the base of the power amplification transistor PA2 through the matching circuit **251**. Then, the power amplification transistor PA2 outputs a signal, obtained by amplifying the RF signal, from the collector of the power amplification transistor PA2.

The power supply voltage V_{CC} is supplied to the collector of the power amplification transistor PA3 through the inductor **221**. Further, the bias current is supplied from the bias circuit **242** to the base of the power amplification transistor PA3. Further, the RF signal output from the power amplification transistor PA1 is input to the base of the power amplification transistor PA3 through the matching circuit **252**. Then, the power amplification transistor PA3 outputs a signal, obtained by amplifying the RF signal, from the collector of the power amplification transistor PA3. Note that, since the bias current is not supplied from the bias circuit **242** in the low power mode, the power amplification transistor PA3 does not operate.

The bias circuit **240** generates a bias current according to the bias voltage V_{BIAS1} to supply the bias current to the base of the power amplification transistor PA1. The bias circuit **241** generates a bias current according to the bias voltage V_{BIAS1} to supply the bias current to the base of the power amplification transistor PA2. The bias circuit **242** generates a bias current according to the bias voltage V_{BIAS2} to supply the bias current to the base of the power amplification transistor PA3. Note that, since the bias voltage V_{BIAS2} is the zero level in the low power mode, the bias circuit **242** does not operate. For example, the bias circuits **240** to **242** can be configured by emitter-follower circuits.

FIG. 3 is a diagram showing an example of the configuration of the bias control circuit **200A**. The bias control circuit **200A** includes a control current generating circuit **300**, a control voltage generating circuit **310**, and a bias voltage generating circuit **320**.

The control current generating circuit **300** generates a control current I_{CONT} according to the power supply voltage V_{CC} . The control voltage generating circuit **310** generates a control voltage V_{CONT} according to the power supply voltage V_{CC} based on the control current I_{CONT} . The bias voltage generating circuit **320** generates bias voltages V_{BIAS1} and V_{BIAS2} according to the power supply voltage V_{CC} based on the power mode control voltage V_{MODE} and the control voltage V_{CONT} . The details of each circuit will be described below.

FIG. 4 is a diagram showing an example of the configuration of the control current generating circuit **300A**, the control voltage generating circuit **310A**, and the bias voltage generating circuit **320A** in the bias control circuit **200A**.

The control current generating circuit **300A** includes P-channel FETs (P1 to P3), N-channel FETs (N1 to N4), a constant current source I_A (first constant current source), a constant current source I_B (second constant current source), and a resistor R_C (first resistor).

The gate of the N-channel FET (N1) (first N-channel FET) is supplied with a reference voltage V_{REF} (first reference voltage), the drain is connected to the drain of the P-channel FET (P1), and the source is connected to the constant current source I_A . The reference voltage V_{REF} is, for example, a band-gap voltage generated based on the battery voltage. The gate of the N-channel FET (N2) (second N-channel FET) is supplied with the power supply voltage V_{CC} , the drain is connected to the drain of the P-channel FET (P2), and the source is connected to the constant current source I_B . The resistor R_C is provided between the source of the N-channel FET (N1) and the source of the N-channel FET (N2). The N-channel FETs (N1, N2) are the same size, for example.

The P-channel FET (P1) is diode-connected. The P-channel FET (P2) is also diode-connected. The P-channel FET

(P3) is current-mirror connected to the P-channel FET (P1). The size ratio of the P-channel FETs (P1 to P3) is, for example, 1:1:m1.

The N-channel FET (N3) is diode-connected with the drain connected to the drain of the P-channel FET (P3). The N-channel FET (N4) is current-mirror connected to the N-channel FET (N3) to output the control current I_{CONT} from the drain of the N-channel FET (N4). The size ratio of the N-channel FETs (N3, N4) is, for example, 1:m2.

Here, the currents of the constant current sources I_A and I_B are denoted as I_A and I_B , respectively. Current flowing from the source of the N-channel FET (N2) into the source of the N-channel FET (N1) through the resistor R_C is denoted as I_C . Currents flowing through the P-channel FETs (P1, P2) are denoted as I_D and I_E , respectively. The resistance value of the resistor R_C is denoted as R_C . The source voltages of the N-channel FETs (N1, N2) are denoted as V_A and V_B , respectively. Under this condition, the current flowing through the N-channel FET (N4), i.e., the control current I_{CONT} will be described.

First, $I_A + I_B = I_D + I_E$ is established in the control current generating circuit 300A. Further, $I_A = I_D + I_C$ and $I_B = I_E - I_C$ are established. Then, $I_{CONT} = m1 \times m2 \times I_D$ is established. Note that the current I_D is current (differential current) corresponding to a difference between V_{REF} (first reference voltage) and the power supply voltage V_{CC} .

When $V_{CC} = V_{REF}$, $I_D = I_E$ because $V_A = V_B$, $I_C = (V_B - V_A)/R_C$ becomes zero.

When $V_{CC} > V_{REF}$, $V_B > V_A$, and k becomes positive. Since I_A is a constant current, I_D decreases compared to the case when $V_{CC} = V_{REF}$. Therefore, I_{CONT} decreases as V_{CC} rises. Note that the minimum value of I_D is zero. In other words, the minimum value of I_{CONT} is zero.

When $V_{CC} < V_{REF}$, $V_B < V_A$, and I_C becomes negative. Since I_A is a constant current, I_D increases compared to the case when $V_{CC} = V_{REF}$. Therefore, I_{CONT} increases as V_{CC} drops. Note that maximum value of I_D is $I_D = I_A + I_B$. In other words, the maximum value of I_{CONT} is $I_{CONT} = m1 \times m2 \times (I_A + I_B)$.

Thus, the control current generating circuit 300A generates the control current I_{CONT} varying according to the power supply voltage V_{CC} . Note that I_C that affects the variation of the control current I_{CONT} by $I_C = (V_B - V_A)/R_C$. Therefore, the rate of change of the control current I_{CONT} according to the change in the power supply voltage V_{CC} varies with the value of R_C . Thus, the dynamic range (a V_{CC} range where I_{CONT} varies) of the control current generating circuit 300A can be controlled by the value of R_C . Specifically, when the value of R_C is relatively small, the rate of change of I_{CONT} according to V_{CC} increases and the dynamic range becomes smaller. On the other hand, when the value of R_C is relatively large, the rate of change of I_{CONT} according to V_{CC} decreases and the dynamic range becomes larger.

The control voltage generating circuit 310A includes an operational amplifier OP1, P-channel FETs (P4, P5), and resistors R_F , R_G .

The operational amplifier OP1 is such that the reference voltage V_{REF} is applied to a non-inverting input terminal and an inverting input terminal is connected to an output terminal and one end of the resistor R_F . The other end of the resistor R_F is grounded. The drain of the P-channel FET (P4) is connected to the output terminal of the operational amplifier OP1. The P-channel FET (P5) is current-mirror connected to the P-channel FET (P4), and the drain of the P-channel FET (P5) is connected to one end of the resistor R_G (current-voltage conversion circuit). The size ratio of the

P-channel FETs (P4, P5) is, for example, 1:m3. The output of the control current generating circuit 300A is also connected to one end of the resistor R_G .

Here, the resistance values of the resistors R_F , R_G are denoted as R_F and R_G , respectively. Currents flowing through the P-channel FETs (P4, P5) are denoted as I_F and I_G , respectively. Under this condition, the control voltage V_{CONT} supplied to the bias voltage generating circuit 320A will be described.

The voltage applied to one end of the resistor R_F through a virtual short-circuit of the operational amplifier OP1 becomes V_{REF} . Therefore, I_F is $I_F = V_{REF}/R_F$, and $I_G = m3 \times I_F$. As a result, the voltage at one end of the resistor R_G , i.e., V_{CONT} becomes $V_{CONT} = (I_G - I_{CONT}) \times R_G$.

Thus, the control voltage generating circuit 310A generates the control voltage V_{CONT} based on the reference current I_G according to the reference voltage V_{REF} and the control current I_{CONT} . Note that, since the control current I_{CONT} is current according to the power supply voltage V_{CC} , the control voltage V_{CONT} becomes voltage according to the power supply voltage V_{CC} .

The bias voltage generating circuit 320A includes an operational amplifier OP2, resistors R_X , R_Y , and a switch S1.

The control voltage V_{CONT} is applied to a non-inverting input terminal of the operational amplifier OP2. The operational amplifier OP2 and the resistors R_X , R_Y constitute a non-inverting amplifier circuit. In other words, a bias voltage V_{BIAS} obtained by amplifying the control voltage V_{CONT} is output from an output terminal of the operational amplifier OP2. An output terminal of the operational amplifier OP2 is connected to an output terminal of the bias voltage V_{BIAS1} and one end of the switch S1.

The switch S1 outputs the bias voltage V_{BIAS} or a zero level of voltage as the bias voltage V_{BIAS2} based on the power mode control voltage V_{MODE} . Specifically, in the low power mode, the switch S1 is connected to the ground to output the zero level of voltage as the bias voltage V_{BIAS2} . On the other hand, in the high power mode, the switch S1 is connected to the output terminal of the operational amplifier OP2 to output the bias voltage V_{BIAS} as the bias voltage V_{BIAS2} .

Thus, the bias voltage generating circuit 320A generates the bias voltages V_{BIAS1} and V_{BIAS2} based on the power mode control voltage V_{MODE} and the control voltage V_{CONT} . Note that, since the control voltage V_{CONT} is voltage according to the power supply voltage V_{CC} , the bias voltages V_{BIAS1} and V_{BIAS2} are also voltages according to the power supply voltage V_{CC} . As a result, bias currents generated in the bias circuits 240 to 242 based on the bias voltages V_{BIAS1} and V_{BIAS2} become currents according to the power supply voltage V_{CC} . Accordingly, the bias current is reduced according to a reduction in output power in the power amplifier module 130 where the power supply voltage V_{CC} is controlled according to the level of output power. Thus, since the idle current (current flowing through the power amplification transistors PA1 to PA3 when no RF signal is input) is reduced according to the reduction in output power in the power amplifier module 130, the consumption current can be reduced.

FIG. 5 is a diagram showing another example of the configuration of the control current generating circuit 300B, the control voltage generating circuit 310A, and the bias voltage generating circuit 320A in the bias control circuit 200A. Since the configuration of the control voltage generating circuit 310A and the bias voltage generating circuit

320A shown in FIG. 5 is the same as that shown in FIG. 4, the description thereof will be omitted.

The control current generating circuit 300B shown in FIG. 5 includes P-channel FETs (P6 to P9), N-channel FETs (N5, N6), a current source I5, a phase-compensation capacitor C5, and a resistor R_H (second resistor).

The P-channel FET (P6) (first P-channel FET) is diode-connected. The P-channel FET (P7) (second P-channel FET) is current-mirror connected to the P-channel FET (P6). The gate of the P-channel FET (P8) is connected to the drain of the P-channel FET (P7), and the drain of the P-channel FET (P8) is connected to one end of the resistor R_H. The P-channel FET (P9) is current-mirror connected to the P-channel FET (P8) to output the control current I_{CONT} from the drain of the P-channel FET (P9). The size ratio of the P-channel FETs (P8, P9) is, for example, 1:m4.

The N-channel FET (N5) (third N-channel FET) is such that the gate is connected to one end of the resistor R_H, the drain is connected to the drain of the P-channel FET (P6), and the source is connected to the current source I5. The N-channel FET (N6) (fourth N-channel FET) is such that the power supply voltage V_{CC} is applied to the gate, the drain is connected to the drain of the P-channel FET (P7), and the source is connected to the current source I5.

Here, the current flowing through the P-channel FET (P9), i.e., the control current I_{CONT} will be described, where the resistance value of the resistor R_H is denoted as R_H and the current flowing through the P-channel FET (P8) is denoted as I_H.

The P-channel FETs (P6, P7), the N-channel FETs (N5, N6), and the current source I5 form a circuit constituting an operational amplifier. The voltage at one end of the resistor R_H becomes the power supply voltage V_{CC} through a virtual short-circuit of this operational amplifier. Therefore, the current I_H flowing through the P-channel FET (P8) is I_H=V_{CC}/R_H. As a result, the control current I_{CONT} is I_{CONT}=m4×V_{CC}/R_H.

Thus, the control current generating circuit 300B shown in FIG. 5 generates the control current I_{CONT} varying according to the power supply voltage V_{CC}. Note that the rate of change of the control current I_{CONT} varies with the value of R_H.

In the configuration shown in FIG. 4, the control voltage V_{CONT} is controlled by subtracting the control current I_{CONT} from the reference current I_G, whereas in the configuration shown in FIG. 5, the control voltage V_{CONT} is controlled by adding the control current I_{CONT} to the reference current I_G. In other words, V_{CONT}=(I_G+I_{CONT})×R_G. In the configuration shown in FIG. 5, I_{CONT}=m4×V_{CC}/R_H, resulting in reducing the control current I_{CONT} with a drop in power supply voltage V_{CC}. Therefore, the control voltage V_{CONT} is reduced according to the drop in the power supply voltage V_{CC}. As a result, since the idle current is reduced according to the reduction in output power in the power amplifier module 130, the consumption current can be reduced.

FIG. 6 is a diagram showing still another example of the configuration of the control current generating circuit 300C, the control voltage generating circuit 310A, and the bias voltage generating circuit 320A in the bias control circuit 200A. Note that, since the configuration of the control voltage generating circuit 310A and the bias voltage generating circuit 320A shown in FIG. 6 is the same as that in FIG. 4, the description thereof will be omitted.

The control current generating circuit 300C shown in FIG. 6 includes P-channel FETs (P10, P11), NPN transistors T1, T2, and resistors R_{JB}, R_{JE}, R_{KB}, and R_{KE}.

The NPN transistor T1 (first NPN transistor) is diode-connected in such a manner that the power supply voltage V_{CC} is applied to the collector and the power supply voltage V_{CC} is applied to the base through the resistor R_{JB}. The NPN transistor T2 (second NPN transistor) is current-mirror connected to the NPN transistor T1 through the resistor R_{KB}. The NPN transistors T1 and T2 are, for example, of the same size.

The resistor R_{JB} is provided between the base and the collector of the NPN transistor T1, and the resistor R_{JE} (third resistor) is provided between the emitter of the NPN transistor T1 and the ground. The resistor R_{KB} is provided between the base of the NPN transistor T2 and the collector of the NPN transistor T1, and the resistor R (fourth resistor) is provided between the emitter of the NPN transistor T2 and the ground. For example, the resistors R_{JB} and R_{KB} have the same resistance value. Further, for example, the resistors R_{JE} and R_{KE} have the same resistance value.

The P-channel FET (P10) is diode-connected with the drain connected to the collector of the NPN transistor T2. The P-channel FET (P11) is current-mirror connected to the P-channel FET (P10) to output the control current I_{CONT} from the drain of the P-channel FET (P11). The size ratio of the P-channel FETs (P10, P11) is, for example, 1:m5.

Here, the current flowing through P-channel FET (P11), i.e., the control current I_{CONT} will be described, where the resistance value of the resistor R_J is denoted as R_{JE}, the base-emitter voltage of the NPN transistor T1 is denoted as V_{BE}, and the collector currents of the NPN transistors T1 and T2 are denoted as I_J and I_K, respectively.

When the base current of the NPN transistor T1 is ignored for ease of description, I_J=(V_{CC}-V_{BE})/R_{JE}, where I_K=I_J. Therefore, I_{CONT}=m5×(V_{CC}-V_{BE})/R_{JE}.

Thus, the control current generating circuit 300C shown in FIG. 6 generates the control current I_{CONT} varying according to the power supply voltage V_{CC}. In the configuration shown in FIG. 6, the control voltage V_{CONT} is controlled by adding the control current I_{CONT} to the reference current I_G like in the configuration shown in FIG. 5. In other words, V_{CONT}=(I_G+I_{CONT})×R_G. In the configuration shown in FIG. 6, I_{CONT}=m5×(V_{CC}-V_{BE})/R_{JE}, resulting in reducing the control current I_{CONT} with a drop in power supply voltage V_{CC}. Therefore, the control voltage V_{CONT} is reduced according to the drop in the power supply voltage V_{CC}. As a result, since the idle current is reduced according to the reduction in output power in the power amplifier module 130, the consumption current can be reduced.

FIG. 7 is a diagram showing another example of the configuration of the bias voltage generating circuit 320B. The bias voltage generating circuit 320B shown in FIG. 7 can be used instead of the bias voltage generating circuit 320A shown in FIG. 4 to FIG. 6. Note that the same reference numerals are used for the same elements as those in the bias voltage generating circuit 320A shown in FIG. 4 to FIG. 6 to omit redundant description.

In addition to the configuration of the bias voltage generating circuit 320A shown in FIG. 4 to FIG. 6, the bias voltage generating circuit 320B shown in FIG. 7 includes a resistor R_Z and a switch S2.

The resistors R_Y and R_Z are connected in series and provided between the inverting input terminal and the output terminal of the operational amplifier OP2. The switch S2 is provided between both ends of the resistor R_Z to operate based on the power mode control voltage V_{MODE}. Specifically, the switch S2 is on in the low power mode or off in the high power mode. Therefore, the bias voltage V_{BIAS} generated by the bias voltage generating circuit 320B is low in the

low power mode. This can further reduce the consumption current at the time of low power.

FIG. 8 is a diagram showing another example of the configuration of a bias control circuit 200B. The bias control circuit 200B shown in FIG. 8 includes a temperature compensation circuit 800 in addition to the configuration of bias control circuit 200A shown in FIG. 3. The temperature compensation circuit 800 generates adjustment currents I_{ADJ1} and I_{ADJ2} for adjusting the bias current according to the temperature characteristics of the amplification transistors PA1 to PA3 of the power amplifier circuit 210.

FIG. 9 is a diagram showing an example of the configuration of the temperature compensation circuit 800 and the control voltage generating circuit 310B in the bias control circuit 200B shown in FIG. 8. Note that any of the configurations shown in FIG. 4 to FIG. 7 can be adopted for the control current generating circuit 300 and the bias voltage generating circuit 320.

The temperature compensation circuit 800 includes an operational amplifier OP3, P-channel FETs (P12, P13), N-channel FETs (N7 to N10), a resistor R_L , and a diode D1.

The operational amplifier OP3 is such that the reference voltage V_{REF} is applied to a non-inverting input terminal and an inverting input terminal is connected to an output terminal and one end of the resistor R_L . The other end of the resistor R_L is connected to the anode of the diode D1, and the cathode of the diode D1 is grounded.

The drain of the P-channel FET (P12) is connected to the output terminal of the operational amplifier OP3. The P-channel FET (P13) is current-mirror connected to the P-channel FET (P12), and the drain of the P-channel FET (P13) is connected to the drain of the N-channel FET (N7). The size ratio of the P-channel FETs (P12, P13) is, for example, 1:m6.

The N-channel FET (N7) is diode-connected, and the drain of the N-channel FET (N7) is connected to the drain of the P-channel FET (P13). The N-channel FET (N8) is current-mirror connected to the N-channel FET (N7) to output the adjustment current I_{ADJ1} from the drain of the N-channel FET (N8). The N-channel FET (N9) is current-mirror connected to the N-channel FET (N7), and the drain of the N-channel FET (N9) is connected to the source of the N-channel FET (N10). The gate of the N-channel FET (N10) is connected to the source of the P-channel FET (P19) of the control voltage generating circuit 310B to output the adjustment current I_{ADJ2} from the drain of the N-channel FET (N10). The size ratio of the N-channel FETs (N7, N8, N9) is, for example, 1:m7:m8.

Here, the resistance value of the resistor R_L is denoted as R_L , a forward-drop voltage across the diode D1 is denoted as V_{DT} , and currents flowing through the P-channel FETs (P12, P13) are denoted as I_L and I_M , respectively. Under this condition, the adjustment currents I_{ADJ1} and I_{ADJ2} will be described.

The voltage at one end of the resistor R_L becomes V_{REF} through a virtual short-circuit of the operational amplifier OP3. Further, the voltage at the other end of the resistor R_L becomes V_{DT} . Therefore, $I_L = (V_{REF} - V_{DT}) / R_L$, and $I_M = m6 \times I_L$. As a result, $I_{ADJ1} = m6 \times m7 \times I_L$ and $I_{ADJ2} = m6 \times m8 \times I_L$. Note that the forward-drop voltage V_{DT} varies according to the temperature characteristics of the diode D1. Specifically, for example, V_{DT} has such characteristics that it rises at low temperature and drops at high temperature. Thus, I_{ADJ1} and I_{ADJ2} vary according to the temperature characteristics of the diode D1.

The control voltage generating circuit 310B shown in FIG. 9 includes P-channel FETs (P14 to P19) and a resistor

R_p in addition to the configuration shown in FIG. 4. Note that the same reference numerals are used for the same elements as those in the control voltage generating circuit 310A shown in FIG. 4 to omit redundant description.

The P-channel FETs (P14, P15, P16) are current-mirror connected to the P-channel FET (P4). The P-channel FET (P17) is diode-connected with the source connected to the drain of the P-channel FET (P15) and the drain connected to the drain of the P-channel FET (P16). The P-channel FET (P18) is current-mirror connected to the P-channel FET (P17) with the drain connected to one end of the resistor R_G . The P-channel FET (P19) is such that the reference voltage V_{REF} is applied to the gate, the source and the back gate are connected to the other end of the resistor R_p , and the drain is grounded. The size ratio of the P-channel FETs (P4, P5, P14) is, for example, 1:m3:m9. Further, the size ratio of the P-channel FETs (P17, P18) is, for example, 1:m10.

Here, the resistance values of the resistors R_F , R_G , and R_p are denoted as R_F , R_G , and R_p , respectively. Currents flowing through the P-channel FETs (P4, P5, P14 to P18) are denoted as I_F , I_{G1} , I_{G2} , I_{P1} , I_Q , I_{P2} , and I_R , respectively. Further, current flowing through the resistor R_G is denoted as I_G . Under this condition, the control voltage V_{CONT} supplied to the bias voltage generating circuit 320 will be described.

The voltage applied to one end of the resistor R_F through a virtual short-circuit of the operational amplifier OP1 becomes V_{REF} . Therefore, I_F is $I_F = V_{REF} / R_F$. Further, $I_{G1} = m3 \times I_F$ and $I_{G2} = m9 \times I_F$. Further, $I_{P2} = I_{ADJ2} - I_Q$. As a result, $I_R = m10 \times I_{P2} = m10 \times (I_{ADJ2} - I_Q)$.

When the control current generating circuit 300 has the configuration shown in FIG. 4, $I_G = I_{G1} + I_{G2} + I_R - I_{ADJ1} - I_{CONT} = I_{G1} - I_{CONT} + (I_{G2} - I_{ADJ1}) + m10 \times (I_{ADJ2} - I_Q)$. Then, the control voltage $V_{CONT} = I_G \times R_G$. When the control current generating circuit 300 has the configuration shown in FIG. 5 or FIG. 6, $I_G = I_{G1} + I_{G2} + I_R - I_{ADJ1} + I_{CONT}$. The following description will be made assuming that the control current generating circuit 300 has the configuration shown in FIG. 4.

The temperature compensation circuit 800 and the control voltage generating circuit 310B are designed so that $I_{G2} = I_{ADJ1}$ and $I_Q = I_{ADJ2}$ at a predetermined temperature T. In other words, $I_G = I_{G1} - I_{CONT}$ at the temperature T.

When the temperature is lower than T, since $I_Q > I_{ADJ2}$, I_R becomes zero. Therefore, $I_G = I_{G1} - I_{CONT} + (I_{G2} - I_{ADJ1})$. I_{ADJ1} increases as the temperature rises. Thus, in a range where the temperature is lower than T, I_G decreases according to the rate of change of I_{ADJ1} as the temperature rises.

When the temperature is higher than T, since $I_Q < I_{ADJ2}$, I_R becomes positive. Therefore, $I_G = I_{G1} - I_{CONT} + (I_{G2} - I_{ADJ1}) + m10 \times (I_{ADJ2} - I_Q)$. I_{ADJ2} increases as the temperature rises. Thus, in a range where the temperature is higher than T, I_G decreases according to the rates of change of I_{ADJ1} and I_{ADJ2} as the temperature rises. Note that, since I_R is added to I_G in the range where the temperature is higher than T, the rate of decrease in I_G with a rise in temperature becomes lower than that in the range where the temperature is lower than T.

Thus, the temperature compensation circuit 800 generates the adjustment currents I_{ADJ1} and I_{ADJ2} varying according to the temperature characteristics of the amplification transistors PA1 to PA3. This leads to the adjustment of the bias voltages V_{BIAS1} and V_{BIAS2} supplied to the power amplifier circuit 210 according to the temperature characteristics of the amplification transistors PA1 to PA3.

Further, in the configuration shown in FIG. 9, if the source voltage of the P-channel FETs (P17, P18) is denoted as V_{P1} and the gate-source voltage of the P-channel FET (P19) is denoted as V_{PGS19} , $V_{P1} = V_{REF} + V_{PGS19} + I_P \times R_p$. Note that

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$I_P = I_{P1} - (I_{P2} + I_R)$. Further, if the drain voltage of the N-channel FET (N9) is denoted as V_{N1} and the gate-source voltage of the N-channel FET (N10) is denoted as V_{NGS10} , $V_{N1} = V_{REF} + V_{PGS19} - V_{NGS10}$.

Thus, in the configuration shown in FIG. 9, the source voltage V_{P1} of the P-channel FETs (P17, P18) and the drain voltage V_{N1} of the N-channel FET (N9) are independent of the variation of the battery voltage V_{BAT} . Therefore, the dependence of the control voltage V_{CONT} on the battery voltage V_{BAT} can be reduced.

FIG. 10 is a graph showing simulation results in the low power mode in the configuration shown in FIG. 9. FIG. 11 is a graph showing simulation results in the high power mode in the configuration shown in FIG. 9. In FIG. 10 and FIG. 11, the abscissa indicates power supply voltage V_{CC} [V] and the ordinate indicates bias voltage V_{BIAS} [V].

As shown in FIG. 10, the bias voltage V_{BIAS} decreases with a drop in power supply voltage V_{CC} in a dynamic range of about 1.9 V at any of temperatures 25° C., 85° C., and -20° C. Thus, the consumption current can be reduced during low power. Further, as shown in FIG. 10, the bias voltage V_{BIAS} varies according to the temperature. This can lead to the adjustment of the bias current according to the temperature characteristics of the amplification transistors PA1 to PA3. The same holds true for the high power mode shown in FIG. 11.

The embodiment has been described above. According to the embodiment, the bias voltage V_{BIAS} decreases with a drop in power supply voltage V_{CC} to reduce the bias current. Thus, since the idle current is reduced according to a reduction in output power in the power amplifier module 130 in which the power supply voltage V_{CC} supplied to the power amplification transistors PA1 to PA3 is controlled according to the level of output power, the consumption current can be reduced.

Note that the embodiment is to facilitate the understanding of the present invention, and not to limit the present invention. The present invention can be changed/modified without departing from the scope thereof, and equivalents can also be included in the present invention.

DESCRIPTION OF REFERENCE NUMERALS

100 transmitting unit
110 modulation section
120 power supply control section
130 power amplifier module
140 front-end section
150 antenna
200, 200A, 200B bias control circuit
210 power amplifier circuit
220, 221 inductor
230, 250 to 252 matching circuit
240 to 242 bias circuit
PA1 to PA3 power amplification transistor
300, 300A, 300B, 300C control current generating circuit
310, 310A, 310B control voltage generating circuit
320, 320A, 320B bias voltage generating circuit
800 temperature compensation circuit

What is claimed is:

1. A power amplifier module comprising:

an amplification transistor supplied with a power supply voltage according to a level of output power to amplify a radio-frequency signal;

a bias control circuit for generating a bias voltage according to the power supply voltage, the bias control circuit including:

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a temperature compensation circuit for generating an adjustment current varying according to temperature characteristics of the amplification transistor, whereby the bias voltage according to the power supply voltage is adjusted based on the adjustment current; and

a bias circuit for supplying a bias current according to the bias voltage to the amplification transistor, wherein a current flowing through the amplification transistor when the radio-frequency signal is not input is varied according to the level of output power.

2. The power amplifier module according to claim 1, wherein the bias control circuit further includes:

a control current generating circuit for generating a control current according to the power supply voltage;

a control voltage generating circuit for generating a control voltage according to the power supply voltage based on the control current; and

a bias voltage generating circuit for generating the bias voltage based on the control voltage.

3. The power amplifier module according to claim 2, wherein the control current generating circuit includes:

a differential current generating circuit for generating a differential current corresponding to a difference between a first reference voltage and the power supply voltage; and

a current mirror circuit for generating the control current as a mirror current of the differential current.

4. The power amplifier module according to claim 3, wherein the differential current generating circuit includes:

a first N-channel FET with a gate supplied with the reference voltage;

a second N-channel FET with a gate supplied with the power supply voltage;

a first constant current source connected to a source of the first N-channel FET;

a second constant current source connected to a source of the second N-channel FET; and

a first resistor provided between the sources of the first and second N-channel FETs, whereby the differential current is generated based on a current in a drain of the first N-channel FET.

5. The power amplifier module according to claim 2, wherein the control current generating circuit includes:

an operational amplifier with the power supply voltage applied to one input terminal thereof; and

a second resistor with one end connected to another input terminal of the operational amplifier and another end grounded,

whereby the control current is generated based on a voltage applied to the one end of the second resistor.

6. The power amplifier module according to claim 5, wherein the operational amplifier includes:

a first P-channel FET diode-connected;

a second P-channel FET current-mirror connected to the first P-channel FET;

a third N-channel FET with a drain connected to a drain of the first P-channel FET and a gate connected to the one end of the second resistor;

a fourth N-channel FET with a drain connected to a drain of the second P-channel FET and a gate supplied with the power supply voltage; and

a current source connected to sources of the third and fourth N-channel FETs.

7. The power amplifier module according to claim 2, wherein the control current generating circuit includes:

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a first NPN transistor with a collector and a base supplied with the power supply voltage;
 a third resistor with one end connected to an emitter of the first NPN transistor and another end grounded;
 a second NPN transistor with a base supplied with the power supply voltage; and
 a fourth resistor with one end connected to an emitter of the second NPN transistor and another end grounded, whereby the control current is generated based on a current in a collector of the second NPN transistor.

8. The power amplifier module according to claim 2, wherein the control voltage generating circuit includes:
 a reference current generating circuit for generating a reference current based on a second reference voltage; and
 a current-voltage conversion circuit for converting, to the control voltage, a current obtained by subtracting the control current from the reference current or by adding the control current to the reference current.

9. The power amplifier module according to claim 2, wherein the bias voltage generating circuit includes:
 an amplifier circuit for amplifying the control voltage by an amplification factor corresponding to an output mode of the output power to generate the bias voltage.

10. The power amplifier module according to claim 9, wherein the bias voltage generating circuit generates first and second bias voltages, the first bias voltage having a non-zero voltage and the second bias voltage having a zero voltage in a low-power output mode, and the first and second bias voltages both having a non-zero voltage in a high-power output mode.

11. A power amplifier module comprising:
 an amplification transistor supplied with a power supply voltage according to a level of output power to amplify a radio-frequency signal;
 a bias control circuit for generating a bias voltage according to the power supply voltage, the bias control circuit including:
 a control current generating circuit for generating a control current according to the power supply voltage;
 a control voltage generating circuit for generating a control voltage according to the power supply voltage based on the control current; and
 a bias voltage generating circuit for generating the bias voltage based on the control voltage; and
 a bias circuit for supplying a bias current according to the bias voltage to the amplification transistor, wherein a current flowing through the amplification transistor when the radio-frequency signal is not input is varied according to the level of output power, wherein the control current generating circuit includes:
 a differential current generating circuit for generating a differential current corresponding to a difference between a first reference voltage and the power supply voltage; and
 a current mirror circuit for generating the control current as a mirror current of the differential current.

12. The power amplifier module according to claim 11, wherein the control current generating circuit includes:
 an operational amplifier with the power supply voltage applied to one input terminal thereof; and
 a second resistor with one end connected to another input terminal of the operational amplifier and another end grounded, whereby the control current is generated based on a voltage applied to the one end of the second resistor.

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13. The power amplifier module according to claim 11, wherein the control current generating circuit includes:
 a first NPN transistor with a collector and a base supplied with the power supply voltage;
 a third resistor with one end connected to an emitter of the first NPN transistor and another end grounded;
 a second NPN transistor with a base supplied with the power supply voltage; and
 a fourth resistor with one end connected to an emitter of the second NPN transistor and another end grounded, whereby the control current is generated based on a current in a collector of the second NPN transistor.

14. The power amplifier module according to claim 11, wherein the differential current generating circuit includes:
 a first N-channel FET with a gate supplied with the reference voltage;
 a second N-channel FET with a gate supplied with the power supply voltage;
 a first constant current source connected to a source of the first N-channel FET;
 a second constant current source connected to a source of the second N-channel FET; and
 a first resistor provided between the sources of the first and second N-channel FETs, whereby the differential current is generated based on a current in a drain of the first N-channel FET.

15. The power amplifier module according to claim 12, wherein the operational amplifier includes:
 a first P-channel FET diode-connected;
 a second P-channel FET current-mirror connected to the first P-channel FET;
 a third N-channel FET with a drain connected to a drain of the first P-channel FET and a gate connected to the one end of the second resistor;
 a fourth N-channel FET with a drain connected to a drain of the second P-channel FET and a gate supplied with the power supply voltage; and
 a current source connected to sources of the third and fourth N-channel FETs.

16. The power amplifier module according to claim 11, wherein the control voltage generating circuit includes:
 a reference current generating circuit for generating a reference current based on a second reference voltage; and
 a current-voltage conversion circuit for converting, to the control voltage, a current obtained by subtracting the control current from the reference current or by adding the control current to the reference current.

17. The power amplifier module according to claim 11, wherein the bias voltage generating circuit includes:
 an amplifier circuit for amplifying the control voltage by an amplification factor corresponding to an output mode of the output power to generate the bias voltage.

18. The power amplifier module according to claim 17, wherein the bias voltage generating circuit generates first and second bias voltages, the first bias voltage having a non-zero voltage and the second bias voltage having a zero voltage in a low-power output mode, and the first and second bias voltages both having a non-zero voltage in a high-power output mode.

19. A power amplifier module comprising:
 an amplification transistor supplied with a power supply voltage according to a level of output power to amplify a radio-frequency signal;
 a bias control circuit for generating a bias voltage according to the power supply voltage, the bias control circuit including:

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a control current generating circuit for generating a control current according to the power supply voltage, the control current generating circuit including:
 a first NPN transistor with a collector and a base supplied with the power supply voltage;
 a third resistor with one end connected to an emitter of the first NPN transistor and another end grounded;
 a second NPN transistor with a base supplied with the power supply voltage; and
 a fourth resistor with one end connected to an emitter of the second NPN transistor and another end grounded,
 whereby the control current is generated based on a current in a collector of the second NPN transistor;
 a control voltage generating circuit for generating a control voltage according to the power supply voltage based on the control current; and
 a bias voltage generating circuit for generating the bias voltage based on the control voltage; and

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a bias circuit for supplying a bias current according to the bias voltage to the amplification transistor, wherein a current flowing through the amplification transistor when the radio-frequency signal is not input is varied according to the level of output power.

20. The power amplifier module according to claim **19**, wherein the control voltage generating circuit includes:

a reference current generating circuit for generating a reference current based on a second reference voltage; and

a current-voltage conversion circuit for converting, to the control voltage, a current obtained by subtracting the control current from the reference current or by adding the control current to the reference current.

21. The power amplifier module according to claim **19**, wherein the bias voltage generating circuit includes:

an amplifier circuit for amplifying the control voltage by an amplification factor corresponding to an output mode of the output power to generate the bias voltage.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 9,461,594 B2
APPLICATION NO. : 14/589376
DATED : October 4, 2016
INVENTOR(S) : Tabei

Page 1 of 1


It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

Column 5, Line 29: please delete “k” and replace it with -- I_C --

Column 8, Line 14: please delete “R” and replace it with -- R_{KE} --

Signed and Sealed this
Seventh Day of February, 2017

A handwritten signature in black ink, reading "Michelle K. Lee". The signature is written in a cursive style with a large, stylized "M" and "L".

Michelle K. Lee
Director of the United States Patent and Trademark Office